

# Ptychographic wavefront sensor for high-NA EUV inspection and exposure tools

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## ABSTRACT

We present a novel approach for wavefront sensing based on scanning diffraction imaging suitable for high-NA optics inspection, where common metrology techniques show limitations. This approach employs ptychography, whereby a well-characterized object is scanned at the focus of the aberrated test optic, and the resulting scattered light is captured on a CCD. Under the Fresnel approximation, the diffraction patterns are processed in an iterative algorithm to reconstruct the test optic aberrations. We discuss the applicability of this wavefront metrology, present numerical simulations that validate the reconstruction, and show first experimental results from an optical prototype.

## 1. INTRODUCTION

As EUV inspection and exposure tools move to larger numerical apertures to accommodate smaller critical dimensions, it becomes increasingly difficult to design a reliable optical test to measure aberrations in these tools. Existing wavefront sensing techniques such as lateral shearing interferometry (LSI) and Hartman sensors suffer more and more from systematic aberrations caused by large wavefront curvatures and low photon flux.

To address these issues, we explore a novel approach based diffraction imaging that is theoretically independent of wavefront curvature and has much more relaxed flux requirements. Although this sensor requires multiple images, the goal is to leverage the precision of mechanical stages and increasingly abundant computational power in order to efficiently reconstruct the wavefront using an iterative algorithm.

## 2. PTYCHOGRAPHY

Recently, a new technique extending coherent diffraction imaging was introduced and coined ptychography by Rodenburg<sup>1</sup> (from the greek *ptychos*—“to fold”), also known as scanning coherent diffraction imaging. This new technique has attracted a lot of attention, not only for its lensless imaging capabilities, but also for its ability to simultaneously reconstruct the probe (the incoming beam) and the object.

The principle of ptychography is to record the diffraction pattern of an object in the far-field (Fraunhofer regime) for different relative lateral position of the object and the probe.

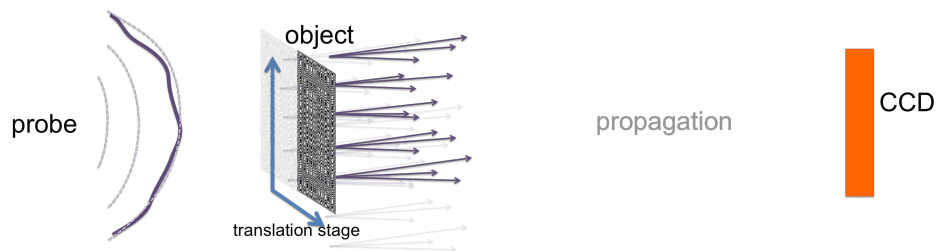


Figure 1. Principle of ptychography.

By scanning the relative position between the probe and the object, ptychography gathers multiple overlapping diffraction patterns and uses an iterative procedure (partially described in Fig. 2, detailed in the literature<sup>2</sup>) that can reliably reconstruct aberrations present in the probe beam, whereas a very good *a priori* knowledge of the probe beam is required in non-scanning techniques such as coherent diffraction imaging. In addition, having overlapping images speeds up the iterative reconstruction process by reducing the presence of local minima, a common problem of most phase retrieval algorithms.

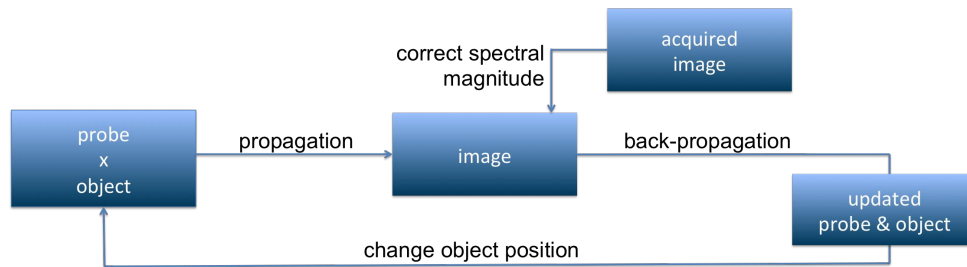


Figure 2. Iterative reconstruction algorithm of the object and probe.

The reconstructions is resolved in amplitude and phase, hence allowing to determine the wavefront of the probe at the object.

### 3. PROBE RECONSTRUCTION

While the initial purpose of ptychography is to reconstruct an object based on its far field diffraction pattern with little knowledge of the object and good knowledge of the probe<sup>3</sup>, the technique can be used in a reciprocal manner, namely by using a well-known object and an unknown probe. Here, the probe is the point spread function of the aberrated test optic. This principle has already been used to characterize high-resolution X-Ray diffraction lenses<sup>4</sup> as well as a focused X-Ray free-electron laser beam<sup>5</sup>. However, in both cases, the numerical aperture of the optics under study was rather limited ( $NA \ll 0.5$ ), allowing the use of far-field approximation (the detection is made several meters downstream). In addition, an increased numerical aperture means that the propagation distance becomes a great concern because of limited sensor size.

However, coherent diffraction imaging does not necessarily require working in the far-field; the use of focused beam and a detection scheme in the Fresnel regime has been proved successful<sup>6</sup>, even outperforming common phase retrieval procedure due to the curvature of the field at the object which can reinforce the uniqueness of a solution to the phase problem.

### 4. SIMULATIONS

We have first performed numerical simulations to show that given incomplete or altered information about the probe beam, the ptychographic iteration (PIE) algorithm will converge to the solution using a propagation method based on Fresnel propagation kernel rather than using the more common Fraunhofer propagation. Using a variety of objects, we were able to faithfully reconstruct an a aberrated probe using only partial knowledge, such as the beam intensity profile at the detector when no object is present and a coarse estimate of the wavefront curvature (Fig. 3).

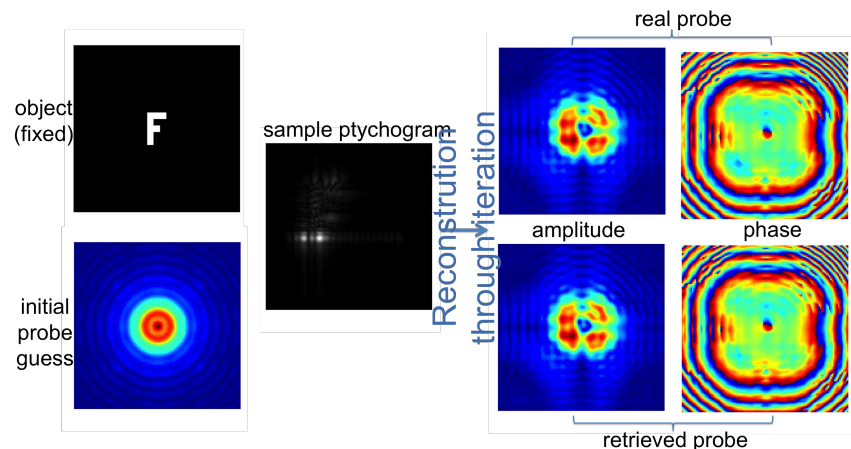


Figure 3. Simulations showing that the phase of the probe can be accurately reconstructed through ptychographic measurements.

We have used the results of the simulations to determine acceptable experimental conditions. Even it is not possible to determine *a priori* which are the sample objects that are the most suitable for probe inspection with full confidence, it seems though that asymmetric objects perform better than objects that have high regularity, while the spectral content of the object does not seem to improve convergence, stability or accuracy of the iterative reconstruction algorithm (Fig. 4).

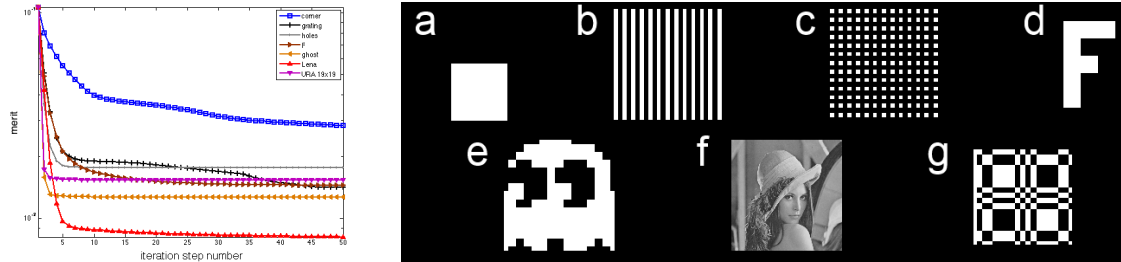


Figure 4. Convergence rates for various simulations of ptychographic reconstructions using different kind of objects (left). Objects used for the simulations : a) a corner; b) a grating; c) a grid of dots; d) a F pattern; e) a "ghost" pattern; f) standard Lena image; g) a (modified) uniformly redundant array (right). The apparent complexity of the object has an influence on the convergence of the algorithm, but not necessarily its spectral content.

It also appears that the number of steps performed does not have a real influence on the reconstruction, provided that the probe is sufficiently sampled, with sufficient overlap between objects positions. Still, the rate of convergence does not guaranty the accuracy of the reconstruction, especially in the case of real data, since many factors such as noise, positioning error and undesired effects such as raster grid pathology may compromise the validity of the resulting wavefront determination.

One drawback of ptychography in the Fresnel regime it requires a minimum grid size to properly sample the quadratic phase<sup>7</sup> of the wavefront, in order to faithfully represent the strong curvature of the field without aliasing. This results in an extra computational burden compared to Fraunhofer regime calculations, but the overhead is not critical for practical applications.

## 5. EXPERIMENTS IN THE VISIBLE RANGE

To validate the results from simulations, we have built an optical prototype using a coherent, monochromatic visible light source (He-Ne laser with  $\lambda=633$  nm).

The light source is spatially filtered (with a pinhole) then focused, using a Fresnel zone plate, onto an object placed on a translation stage, and the exit wave is recorded on a CCD further apart (Fig. 5).

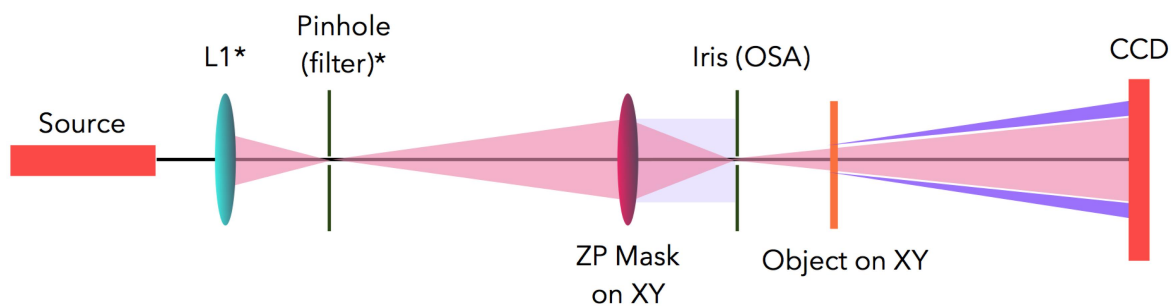


Figure 5. Layout of the visible light prototype for wavefront reconstruction.

A zone plate is used as the test optic to emulate the aberrations of the optics under test. It is chosen for a set of zone plates that we designed featuring programmed wavefront aberrations, with pure or a mixture of Zernike terms with magnitudes ranging from 20 to 200 mWaves. The zone plates have a focal length of 19.3 mm, a 30%

by radius central obscuration and a numerical aperture of 0.1, slower than 0.5 to cope with stages dimensions and detector size. An order sorting aperture isolates the first order focus of the zone plate to mitigate the effect of flare caused by DC and higher order diffraction from the zone plate.

To use a common imaging configuration, we have used a object of size  $300\text{ }\mu\text{m}$  representing a pixelated ghost, placed slightly before the zone plate focus ( $18.25\text{ mm}$ ), having a footprint at the object of about  $300\text{ }\mu\text{m}$ . We have also considered other objects for this study (Fig. 6) such as a grating, a checkerboard or a modified uniformly redundant array<sup>8</sup>, whose Fourier Transform has a flat spectrum; these objects will be studied in further experiments.

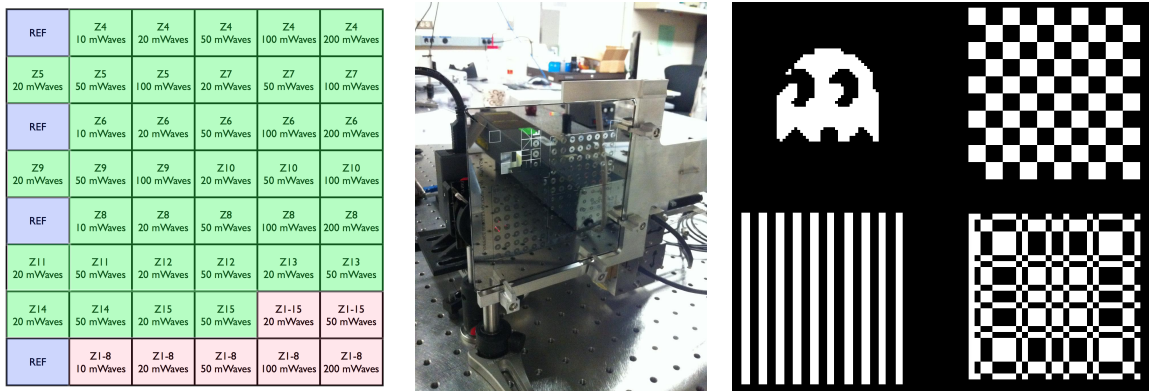


Figure 6. Set of Fresnel zone plates with programmed Zernike terms (Z1-15) to simulate optics with wavefront error (left), picture of the optical setup (center), and a variety of objects used for data acquisition (right).

Due to the use of relatively large high-NA zone plates and rather large focal length to mimic the scale of EUV optics, a large-area detector is required. The camera we used (PIXELINK PL-D725) has a sensing area of  $12.4\times9.8\text{ mm}^2$  with a pixel size of  $4.8\text{ }\mu\text{m}$  and was placed  $40\text{ mm}$  downstream the object.

The number of ptychograms was chosen for the object so as to provide at least 60% overlap between adjacent object positions and make sure that there are no overall dark zone in the probe overlapping the object. Sixteen ptychograms were acquired, scanning horizontally and vertically with a step size of  $100\text{ }\mu\text{m}$ . Simulations of the optical properties of the probe match the acquired data (Fig. 7), and we are currently working towards full reconstruction of the probe.

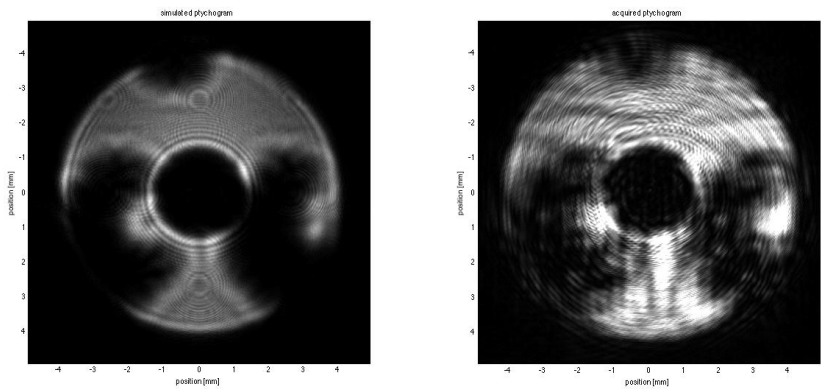


Figure 7. Matching simulation (left) and experimental data (right) for visible range experiments.

We have tried to expand the field of view of a smaller camera sensor by moving it on a stage and stitch the images, but it proved extremely challenging due experimental annoyance such as flare or the impossibility to efficiently register the pixels due to the inherent lack of sharp features in the Fresnel regime.

## 6. DISCUSSION

A key advantage of the ptychographic wavefront sensor is its ability to operate with a variety of test objects. In this light, we note that this sensor can emulate many other wavefront sensing schemes. For example, in the case that the scanned object is an 1-dimensional edge, the ptychograms are identical to the dataset acquired by the familiar knife-edge test. On the other hand, if the object is a 2-dimensional array, the sensor bears resemblance to either lateral shearing interferometry<sup>9</sup> or a Hartman sensor. In each of these cases, the ptychographic sensor can be used in tandem with these corresponding tests since the required datasets are identical. Furthermore, this allows direct comparison to existing techniques using the same acquired data, while ptychography does not require some of the strong assumptions that are necessary to direct techniques. In some cases, direct determination can be used to provide a good initial guess before being refined using the iterative process.

Whereas ptychography has first been introduced of as a means to reconstruct images without using optical elements because these are either unavailable or because they would require extreme manufacturing quality, it might provide a powerful method to assess the quality of optics whenever the use of those cannot be avoided, as in EUV lithography tools.

Ptychographic wavefront reconstruction can be seen as a superset of existing techniques, the innovation being that it allows to drop most of the restricting hypotheses required in the analytical treatment of common techniques, at the expense of increased computational power, while at the same time the position variety helps keeping the number of iteration and the error figure low.

We want to use the results from visible light experiments to figure out what kind of object provides faster and/or more precise wavefront reconstruction. Then, we would like to extend the analysis to EUV using coherent multiplexing, *i.e.* to cases where the optics under test is illuminated by an array of pinholes, in order to increase flux efficiency without sacrificing accuracy.

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